TITLE OF THE INVENTION

MAGNETIC BEARING DEVICE

BACKGROUND OF THE INVENTION

The present invention relates to magnetic bearing

5 devices, and more particularly to a magnetic bearing

device for magnetically levitating a rotary body by

contactlessly supporting the body with a plurality of

magnetic bearings with respect to an axial direction and

two radial directions orthogonal to each other and to

10 the axial direction.

Already known as such magnetic bearing devices are

those having five control axes, i.e., a control axis in

an axial direction and two control axes respectively in

two radial directions at each of two locations in the

15 axial direction.

Magnetic bearing devices of the five-axis control

type comprise an axial magnetic bearing for

contactlessly supporting a rotary body with respect to

the direction of axial control axis, two radial magnetic

20 bearings for contactlessly supporting the rotary body

with respect to the two directions of radial control

axes orthogonal to each other at each of the two loca-

tions in the axial direction, and protective bearings

(touchdown bearings) serving as mechanical restraining means for mechanically determining the movable ranges of the rotary body in the axial direction and the radial directions. The axial magnetic bearing comprises a pair

5   of electromagnets so arranged as to hold the rotary body at opposite sides thereof in the direction of axial control axis for magnetically attracting the body. Each of the radial magnetic bearings comprises a pair of electromagnets so arranged as to hold the rotary body at

10 opposite sides thereof in the direction of radial control axis concerned for magnetically attracting the body. Furthermore, the magnetic bearing device comprises a position detector serving as position detecting means for detecting the position of the rotary

15 body with respect to the direction of each of the five control axes, and an electromagnet controller serving as electromagnet control means for controlling the pair of electromagnets for the control axis based on the result of detection of the position by the position detector.

20 The position detector in the direction of axial control axis comprises one axial position sensor opposed to the end face of the rotary body to be detected from the direction of axial control axis. The position detector in the direction of each radial control axis comprises a

pair of radial position sensors opposed to the rotary body and so arranged as to hold the body at opposite sides thereof in the direction of the control axis. The electromagnet controller comprises a proportional

5 operation unit, differential operating unit and integral operating unit.

With respect to the direction of each control axis, the magnetic bearing device described has a mechanical central position for the movable range determined by the

10 protective bearings, a magnetic central position relative to the positions of the electromagnets of the magnetic bearing, and central position relative to the sensors, i.e., relative to the positions of the position sensors. The mechanical central position in the

15 direction of each control axis is the position of center of the movable range determined by the protective bearings. The magnetic central position with respect to the direction of each control axis is the position of the center of the pair of electrode magnets as arranged

20 in the direction of the control axis. The central position relative to the sensor in the direction of the axial control axis is such that the gap (clearance) between the position detecting end face of the rotary body and the axial position sensor has a predetermined

value. The central position relative to the sensors in the direction of each radial control axis is the position of center of the pair of radial position sensors as arranged in the direction of the control

5 axis. The magnetic bearing device is so designed that the mechanical central position, the magnetic central position and the central position relative to the sensors are all in coincidence, whereas an error is likely to occur between the centers owing to

10 manufacturing errors or assembling errors.

With the conventional magnetic bearing device, the electromagnets of the magnetic bearings are so controlled that the rotary body will be held at the central position relative to the sensors which is the

15 designed central position, that is, the center of the rotary body will be at the central position relative to the sensors. Accordingly, the rotary body can not be held at the mechanical central position if the central position relative to the sensors is not in coincidence

20 with the mechanical central position. When the difference of the mechanical central position of the rotary body from the central position relative to the sensors is great in this case, the clearance between the rotary body and the protective bearing diminishes

locally to result in troubles.

SUMMARY OF THE INVENTION

An object of the present invention is to provide a magnetic bearing device capable of magnetically

5   levitating a rotary body approximately at the mechanical central position of the device easily.

The present invention provides a magnetic bearing device for magnetically levitating a rotary body by contactlessly supporting the body with magnetic

10 attraction of pairs of electromagnets with respect to an axial direction and two radial directions orthogonal to each other and to the axial direction, the rotary body having movable ranges in the three supporting directions determined by mechanical restraining means, the magnetic

15 bearing device being characterized in that the device comprises a pair of electromagnets so arranged as to hold the rotary body at opposite sides thereof in the direction of each of control axes in the respective three supporting directions, means for detecting the

20 position of the rotary body in the direction of the control axis and electromagnet control means having at least an integral operation unit for controlling the electromagnets based on the result of detection of the position by the position detecting means, the

electromagnet control means comprising a target
levitated position setting means for setting as a target
levitated position of the rotary body in the direction
of the control axis the position of the rotary body
5   corresponding to the median of an integral output which
is the output of the integral operation unit when the
rotary body is magnetically levitated in the vicinity of
one of limit positions in the direction of the control
axis determined by the mechanical restraining means and
10 an integral output of the integral operation unit when
the rotary body is magnetically levitated in the
vicinity of the other limit position.

The pair of electromagnets to be used for each
control axis are usually identical in characteristics.
15 The electromagnet control means supplies to each
electromagnet an energizing current comprising the
combination of a predetermined steady-state current and
a control current which varies depending on the position
of the rotary body in the direction of the control axis.
20 The steady-state current values for the pair of
electromagnets are equal to each other, and the control
currents therefor are equal to each other in absolute
value but opposite in sign.

In the case where no force other than the magnetic

attraction of the electromagnets acts on the rotary body as in the case of a horizontal control axis, and when the rotary body is contactlessly supported at a position with respect to the direction of the control axis, the

5   magnetic attracting forces of the two electromagnets on the rotary body are equal to each other. Further the magnetic attraction of each electromagnet is in proportion to the square of the magnitude of the energizing current of the electromagnet and in inverse

10   proportion to the size of the gap between the electromagnet and the rotary body. When the rotary body is supported at the magnetic central position, the gaps between the rotary body and the respective electromagnets are equal to each other in size, with the

15   result that the energizing current values of the respective electromagnets are equal to each other. Thus, the control current values for the respective electromagnets are zero. When the rotary body is supported as shifted toward either direction from the

20   magnetic central position, the gaps between the rotary body and the electromagnets are different from each other in size, so that the energizing current values of the electromagnets differ from each other. Accordingly the control current values for the electromagnets differ

from each other. The control current value of each

electromagnet is proportional to the displacement of the

rotary body from the magnetic central position. Further

the control current value of one of the electromagnets

5 is in proportion to the output of the integral operation

unit of the electromagnet control means, i.e., the

integral output. When the position where the rotary

body is supported is shifted from one limit position to

the other limit position, therefore, the integral output

10 varies linearly. For this reason, the position of the

rotary body corresponding to the median of the integral

output obtained when the rotary body is magnetically

levitated in the vicinity of one limit position and the

integral output obtained when the rotary body is

15 magnetically levitated in the vicinity of the other

limit position is approximately the mechanical central

position, with the result that by taking the position

corresponding to the median as a target levitated

position, the rotary body can be magnetically levitated

20 approximately at the mechanical central position.

In the case where the rotary body is subjected to

gravity in addition to the magnetic attraction of

electromagnets as in the case of a vertical control

axis, and when the rotary body is contactlessly

supported at a position in the direction of the control

axis, the upward magnetic attraction afforded by the

upper electromagnet is in balance with the combination

of the downward magnetic attraction of the lower

5   electromagnet and gravity. With the rotary body

supported at the magnetic central position, therefore,

the control current for the upper electromagnet has a

positive value, and the control current for the lower

electromagnet is of a negative value, so that the

10   integral output is not zero. Even in this case,

however, the integral output varies linearly if the

position where the rotary body is supported is shifted

from one limit position to the other limit position. As

in the foregoing case, the rotary body can accordingly

15   be magnetically levitated approximately at the

mechanical central position by taking as the target

levitated position a position corresponding to the

median of the integral output obtained when the rotary

body is magnetically levitated in the vicinity of one

20   limit position and the integral output obtained when the

rotary body is magnetically levitated in the vicinity of

the other limit position.

The same is true of the case wherein the control

axis is oblique; regardless of the posture of the rotary

body as installed, the body can be magnetically

levitated approximately at the mechanical central

position.

The magnetic bearing device is usually divided into

5   a machine main body comprising a rotary body,

electromagnets of magnetic bearings, protective bearings

and position sensors included in position detecting

means, and a controller comprising electromagnet control

means, a sensor circuit included in the position

10   detecting means for driving the position sensors and

calculating the position of the rotary body based on the

outputs of the position sensors, etc. The main body and

the controller are interconnected by a cable. Further

while the magnetic bearing device is in use, there

15   arises a need to replace the controller by another one

of the same type. Even if of the same type, machine

main bodies are not always identical in the relationship

between the mechanical central position, magnetic

central position and central position relative to the

20   sensors. However, the machine main bodies remain

unchanged in the relationship between these three

positions.   Accordingly, insofar as the combination of

the machine main body and the controller remains

unchanged, a target levitated position may be set as

described above when the magnetic bearing device is to

be initiated into operation for the first time. It is

then possible to subsequently magnetically levitate the

rotary body approximately at the mechanical central

5 position by using this target levitated position. If

the combination of machine main body and controller is

changed, however, the target levitated position is not

set in the new controller, which therefore fails as it

is to magnetically levitate the rotary body at the

10 mechanical central position. Even in such a case,

nevertheless, a target levitated position can be set in

the manner described above to magnetically levitate the

rotary body approximately at the mechanical central

position.

15 When the magnetic bearing device of the present

invention is to be initiated into operation for the

first time, or when the combination of the machine main

body and the controller is changed, the rotary body can

be magnetically levitated approximately at the

20 mechanical central position by the simple procedure of

moving the rotary body from one of limit positions in

the direction of control axis to the other limit

position, regardless of the posture of the rotary body

as installed. Accordingly it is unlikely that the

clearance between the rotary body and mechanical restraining means will diminish locally as experienced in the prior art to result in various troubles.

For example, the target position setting means is

5   adapted to position the rotary body at said one limit position, thereafter magnetically levitate the rotary body in the vicinity thereof, obtain the integral output at this time to store the output as a first limit position integral output in a memory, gradually shift

10   the magnetically levitated position of the rotary body toward said other limit position, determine the position of the rotary body every time the rotary body is so shifted by a small distance at a time and the corresponding integral output for storage as an

15   intermediate position and an intermediate position integral output in the memory, move the rotary body to said other limit position, thereafter magnetically levitate the rotary body in the vicinity thereof, obtain the integral output at this time for use as a second

20   limit position integral output, determine the median of the first limit position integral output and the second limit position integral output, and select the output most proximate to the median from among the intermediate position integral outputs stored in the memory to

determine the intermediate position corresponding to the

selected intermediate position integral output as the

target levitated position.

BRIEF DESCRIPTION OF THE DRAWINGS

5   FIG. 1 is a view in vertical section of the main

portion of mechanical assembly of a magnetic bearing

device embodying the present invention;

FIG. 2 is a view in cross section of the same;

FIG. 3 is a block diagram showing an example of

10 electrical construction of the magnetic bearing device;

FIG. 4 is a block diagram of the portion of

controller of FIG. 3 relating to a pair of axial

electromagnets;

FIG. 5 is a block diagram showing the function of

15 the portion of DSP in FIG. 4; and

FIG. 6 is a block diagram of the portion of

controller of FIG. 3 relating to a pair of radial

electromagnets.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

20   Referromg to the drawings, a description will be

given below of a magnetic bearing device of the five-

axis control type embodying the present invention.

FIG. 1 is a view in vertical section of the main

porion of mechanical assembly of the magnetic bearing

device of the five-axis control type embodying the
invention, FIG. 2 is a cross sectional view of the same,
and FIG. 3 is a block diagram of an example of
electrical construction of the same.

5   The magnetic bearing device comprises a machine main
body 1 and a controller 2 which are interconnected by a
cable. The bearing device is of the vertical type
wherein a rotary body 5 in the form of a vertical shaft
is rotatable within a casing 4 in the form of a vertical
10 hollow cylinder. In the following description, the axis
of the rotary body 5 in its axial direction (vertical
direction) will be referred to as the Z-axis, and axes
in two radial directions (horizontal directions)
orthogonal to each other and orthogonal to the Z-axis
15 will be referred to as the X-axis and Y-axis,
respectively.

The machine main body 1 has an axial magnetic
bearing 6 for supporting the rotary body 5 with respect
to the direction of Z-axis without contact therewith
20 (i.e., contactlessly), upper and lower two radial
magnetic bearings 7, 8 for contactlessly supporting the
rotary body 5 respectively at two locations in the axial
direction, with respect to the directions of X-axis and
Y-axis, a position detector 9 for detecting the

displacement of the rotary body 5 in the axial direction
and the position of the rotary body 5 with respect to
the X-axis and Y-axis directions at the two locations, a
built-in electric motor 10 for rotating the rotary body

5   5 at a high speed, and upper and lower two protective
bearings 11, 12 serving as restraining means for
limiting the movable ranges of the rotary body 5 with
respect to the axial direction and radial directions and
mechanically supporting the rotary body 5 at limit

10   positions of the movable ranges when the magnetic
bearings 6, 7, 8 become unable to support the rotary
body 5. The Z-axis serves as a control axis in the
axial direction. A control axis in the X-axis direction
at the location of the upper bearing 7 will be referred

15   to as the "upper X-axis", a control axis in the Y-
direction at the same location as the "upper Y-axis," a
control axis in the X-axis direction at the location of
the lower bearing 8 as the "lower X-axis", and a control
axis in the Y-direction at the same location as the

20   "lower Y-axis."

The controller 2 comprises a sensor circuit 13,
bearing drive circuit 14, inverter 15 and DSP board 16.
The DSP board 16 has a DSP 18 serving as digital
processing means programmable with software, ROM 31,

flash memory 19 serving as memory means, AD converter 20 and DA converter 21. DSP stands for a digital signal processor, which is specific hardware adapted to receive digital signals and produce digital signals and

5   programmable with software and operable for high-speed real-time processing.

The position detector 9 comprises one axial position sensor 23 for detecting the position of the rotary body 5 with respect to the Z-axis direction, and upper and

10   lower two radial position sensor units 24, 25 for detecting the position of the rotary body 5 with respect to the X-axis and Y-axis directions.

The axial magnetic bearing 6 comprises a pair of axial electromagnets 26a, 26b so arranged as to hold a

15   flange 5a of the rotary body 5 at opposite sides of the flange in the Z-axis direction for magnetically attracting the body 5, the flange 5a being formed on a lower portion of the rotary body 5 integrally therewith. The axial electromagnets are collectively designated by

20   the reference numeral 26. The pair of axial electromagnets 26 are identical in characteristics.

The axial position sensor 23 is disposed as opposed to the lower end face of the rotary body 5 from therebelow with respect to the Z-axis direction and

produces a distance signal in proportion to the size of the gap between the lower end face of the body 5 and the sensor 23.

The two radial magnetic bearings 7, 8 are arranged
5   above the axial magnetic bearing 6 and vertically spaced apart from each other, with the motor 10 interposed therebetween. The upper radial magnetic bearing 7 comprises a pair of upper radial electromagnets 27a, 27b so arranged as to hold the rotary body 5 at opposite
10   sides thereof in the X-axis direction for magnetically attracting the body 5, and a pair of upper radial electromagnets 27c, 27d so arranged as to hold the rotary body 5 at opposite sides thereof in the Y-axis direction for magnetically attracting the body 5. These
15   radial electromagnets are designated collectively by the reference numeral 27. Similarly, the lower radial magnetic bearing 8 comprises two pairs of lower radial electromagnets 28a, 28b, 28c, 28d. These radial electromagnets are designated collectively also by the
20   reference numeral 28. At least one pair of electromagnets on the same control axis used in each of the radial bearings 7, 8 are identical in characteristics. Preferably, all the radial electromagnets 27, 28 used are identical in

characteristics.

The upper radial position sensor unit 24 is disposed in the vicinity of the upper radial magnetic bearing 7 and comprises a pair of upper radial position sensors 29a, 29b so arranged as to hold the rotary body 5 at opposite sides thereof in the X-axis direction in the vicinity of the electromagnets 27a, 27b in the X-axis direction, and a pair of upper radial position sensors 29c, 29d so arranged as to hold the rotary body 5 at opposite sides thereof in the Y-axis direction in the vicinity of the electromagnets 27c, 27d in the Y-axis direction. These radial position sensors are designated collectively by the reference numeral 29. Similarly, the lower radial position sensor unit 25 is disposed in the vicinity of the lower radial magnetic bearing 8 and comprises two pairs of lower radial position sensors 30a, 30b, 30c, 30d. These radial position sensors are designated collectively also by the reference numeral 30. The radial position sensors 29, 30 each produce a distance signal in proportion to the size of the gap between the outer periphery of the rotary body 5 and the sensor.

The electromagnets 26, 27, 28 and the position sensors 23, 29, 30 are fixed to the casing 4.

The upper protective bearing 11 comprises an antifriction bearing such as a deep groove ball bearing and is adapted to support a radial load. The bearing 11 has an outer ring 11a secured to the casing 4 and an inner ring 11b disposed as opposed to the outer peripheral surface of the rotary body 5 with a suitable gap provided therebetween. The lower protective bearing 12 comprises an antifriction bearing such as a deep groove ball bearing and is adapted to support both an axial load and a radial load. The bearing 12 has an outer ring 12a secured to the casing 4 and an inner ring 12b provided around an annular grooved portion 17 formed in the outer peripheral surface of the rotary body 5, with a suitable gap provided between the ring 12b and the body 5 axially and radially thereof. The axial movable range of the rotary body 5 is determined by the size of the axial gap between the inner ring 12b of the lower bearing 12 and the rotary body 5, and the radial movable range of the rotary body 5 is determined by the size of the radial gap between the rotary body 5 and each of the inner rings 11b, 12b of the bearings 11, 12. Even when the rotary body 2 is supported by the protective bearings 11, 12 at a limit position of the movable range, the rotary body 5 is spaced apart from

the electromagnets 26, 27, 28 and from the position
sensors 23, 29, 30 and is held out of contact with the
electromagnets 26, 27, 28 and the position sensors 23,
29, 30.

5   The sensor circuit 13 of the controller 2 drives the
position sensors 23, 29, 30 of the position detector 9
and calculates the position of the rotary body 5 with
respect to the Z-axis direction and with respect to the
X-axis direction and the Y-axis direction at the
10   locations of the upper and lower radial position sensor
units 24, 25 based on distance signals output from the
respective position sensors 23, 24, 25, and delivers the
results of calculation, i.e., position signals, to the
DSP 18 via the AD converter 20. The position detector 9
15   and the sensor circuit 13 constitute a position
detecting assembly as position detecting means for
detecting the position of the rotary body 5 with respect
to the direction of each control axis.

      The ROM 31 has stored therein, for example,
20   processing programs for the DSP 18. Stored in the flash
memory 19 are a control parameter table having held
therein control parameters for the magnetic bearings,
bias current value table having held therein the bias
current value to be described later, etc. Based on the

digital position signals representing the position of
the rotary body 5 with respect to the respective control
axes and delivered from the AD converter 20, the DSP 18
feeds energizing current signals for the electromagnets

5   26, 27, 28 of the magnetic bearings 6, 7, 8 to the
bearing drive circuit 14 via the DA converter 21.   The
drive circuit 14 supplies energizing currents based on
the current signals from the DSP 18 to the
electromagnets 26, 27, 28 of the magnetic bearings 6, 7,

10   8, whereby the rotary body 5 is contactlessly supported
at the target levitated position to be described later.
The DSP 18 constitutes an electromagnet controller
serves as electromagnet control means for controlling
the energizing currents to be supplied to the respective

15   electromagnets 26, 27, 28 of the bearings 6,7, 8 based
on the results of detection of the position by the
position detecting means.

     The DSP 18 further outputs a rotational speed
command signal for the motor 10 to the inverter 15,

20   which in turn controls the speed of rotation of the
motor 10 based on this signal.   As a result, the rotary
body 5 as contactlessly supported at the target
levitated position by the magnetic bearings 6, 7, 8 is
rotated at a high speed.

FIG. 4 shows only the portion of the controller 2

which is associated with the control of the pair of

axial electromagnets 26a, 26b of the axial magnetic

bearing 6. With reference to FIG. 4, a description will

5 now be given of the control of the pair of axial

electromagnets 26a, 26b by the controller 2.

First, the sensor circuit 13 detects the position of

the rotary body 5 with respect to the Z-axis direction

from the output signal of the axial position sensor 23

10 and produces a position signal Zs in proportion to this

position. The position signal Zs from the sensor

circuit 13 is converted by the AD converter 20 to a

digital value, which is fed to the DSP 18. As will be

described later, the DSP 18 calculates the displacement

15 of the rotary body 5 from the target levitated position

from the digital position signal Zs, and feeds to the DA

converter 21 a pair of energizing current signals as

control signals corresponding to the respective

electromagnets 26. The first of the energizing current

20 signals, (Io+Ic), is converted by the DA converter 21 to

an analog signal, which is fed as the first energizing

current signal (Io+Ic) to a first power amplifier 35 of

the bearing drive circuit 14. The amplifier 35

amplifies this signal (Io+Ic) and feeds an energizing

current in proportion to this signal to the first

electromagnet 26a. The second of the energizing current

signals, (Io-Ic), is converted by the DA converter 21 to

an analog signal, which is fed as the second energizing

5   current signal (Io-Ic) to a second power amplifier 36 of

the bearing drive circuit 14. The amplifier 36

amplifies this signal (Io-Ic) and feeds an energizing

current in proportion to this signal to the second

electromagnet 26b. Consequently, the rotary body 5 is

10   supported at the target levitated position with respect

to the Z-axis direction.

     FIG. 5 shows the operation of the DSP 18 in the form

of function blocks in the portion of controller 2 shown

in FIG. 4. The DSP 18 functionally comprises

15   subtracting means 22, target levitated position setting

means 32, control current computing means 37 and

energizing current computing means 38. The subtracting

means 22 subtracts the target levitated position Zo

input from the target position setting means 32 as will

20   be described later from the position signal Zs input

from the AD converter 20 to calculate the value ΔZ of

displacement of the rotary body 5 from the target

levitated position and feeds the value ΔZ to the control

current computing means 37. Based on the displacement

value ΔZ from the subtracting means 22, the computing

means 37 calculates a control current value Ic for the

electromagnets 26a, 26b, for example, by PID operation.

The computing means 37 comprises an integral operation

5   unit (integral operation portion) 40, proportional

differential operation unit (proportional differential

operation portion) 41 and addition unit 42. The

integral operation unit 40 calculates an integral

component Ici of the control current value Ic based on

10   the displacement value ΔZ using integral operation

control parameters stored in the table in the flash

memory 19. The proportional differential operation unit

41 calculates a proportional differential component Icpd

of the control current value Ic based on the

15   displacement value ΔZ using proportional operation

control parameters and differential operation control

parameters stored in the table in the flash memory 19.

The addition unit 42 adds the integral component Ici and

the proportional differential component Icpd to

20   calculate the control current value Ic and feeds the

value to the energizing current computing means 38.

Incidentally, the proportional differential operation

unit 41 may be divided into a proportional operation

unit and a differential operation unit to calculate the

control current value Ic by adding up the output of the

proportional operation unit, i.e., a proportional

component, the output of the differential operation

unit, i.e., a differential component, and the output of

5   the integral operation unit 40, i.e., the integral

component Ici. The energizing current computing means

38 adds the control current value Ic from the control

current computing means 37 to a bias current value Io

stored in the table in the flash memory 19 and feeds the

10   resulting value (Io+Ic) to the DA converter 21 as a

first energizing current value. The computing means 38

also subtracts the control current value Ic from the

bias current value Io and feeds the resulting value (Io-

Ic) to the DA converter 21 as a second energizing

15   current value. The target levitated position setting

mans 32 sets the target levitated position to be

described later.

    FIG. 6 shows only the portion of the controller 2

associated with the control of the pair of radial

20   electromagnets 27a, 27b in the X-axis direction of the

upper radial magnetic bearing 7. In this case, the

sensor circuit 13 subtracts the output signal of one of

the pair of radial position sensors 29a, 29b in the X-

axis direction of the upper radial position sensor unit

24 from the other to detect the position of the rotary

body 5 with respect to the X-axis direction at the

location of the upper radial magnetic bearing 7 and

outputs a position signal Xs in proportion to this

5   position. The position signal Xs from the sensor

circuit 13 is converted by the AD converter 20 to a

digital value (digital displacement signal Xs), which is

fed to the DSP 18. The same procedure as in the case of

FIG. 4 then follows. Like parts are designated by like

10   reference numerals or symbols.

The same procedure is followed by the controller

portion associated with the control of the pair of

radial electromagnets 27c, 27d in the Y-axis direction

of the upper radial magnetic bearing 7, the portion

15   associated with the control of the pair of radial

electromagnets 28a, 28b in the X-axis direction of the

lower radial magnetic bearing 8, and the portion

associated with the control of the pair of radial

electromagnets 28c, 28d in the Y-axis direction of the

20   lower radial magnetic bearing 8.

The magnetic bearing device has a mechanical central

position, magnetic central position and a central

position relative to the sensors. The mechanical

central position is the position of the center in the

movable ranges determined by the protective bearings 11,
12. With respect to the axial direction, this position
is such that the inner ring 12b of the lower protective
bearing 12 is positioned axially in the middle of the

5   groove 17 in the rotary body 5, with opposite end faces
of the inner ring 12b axially separated by equal
distances from the side faces of the body 5 defining the
groove 17 and opposed to the respective end faces. With
respect to the radial direction, the center of the

10   rotary body 5 is in coincidence with the centers of the
two protective bearings 11, 12 in this position, with
the inner rings 11b, 12b of the bearings 11, 12 radially
separated from the rotary body 5 by equal distances over
the entire circumference. The magnetic central position

15   is the position of the centers of the respective pairs
of opposed electromagnets 26, 27, 28 of the magnetic
bearings 6, 7, 8. The central position relative to the
sensors is such that with respect to the axial
direction, the axial position sensor 23 is axially

20   separated from the lower end face of the rotary body 5
by a predetermined distance. With respect to the radial
direction, this position is the position of the centers
of respective pairs of opposed position sensors 29, 30
of the radial position sensor units 24, 25.

When the magnetic bearing device described is to be initiated into operation first, a target levitated position is set by the DSP 18 for each control axis, and the magnetic bearings 6, 7, 8 are thereafter controlled

5 so that the rotary body 5 will be supported at the target levitated position.

Before the operation of the bearing device is started first, the magnetic bearings 6,7, 8 and the motor 10 are unenergized, with the rotary body 5 held at

10 a halt as supported by the inner rings 11b, 12b of the protective bearings 11, 12.

When the magnetic bearing device described is to be initiated into operation first, the target levitated position is set, for example, in the order to be

15 described below, i.e., first in the Z-axis direction, then in the X-axis direction and thereafter in the Y-axis direction.

First, the target levitated position is set with respect to the Z-axis direction in the following manner.

20 First, the rotary body 5 is supported at a predetermined temporary levitated position with respect to the X-axis direction and the Y-axis direction. This is done by the target levitated position setting means of each of the control axes, i.e., the X-axis and Y-

axis, feeding the temporary levitated position to the
subtracting means.   The temporary levitated position
with respect to the X-axis direction and the Y-axis
direction is, for example, the central position relative
5   to the sensors in the direction of each of these control
axes.

When the rotary body 5 is supported at the temporary
levitated position with respect to the X-axis and Y-axis
directions, the axial electromagnets are unenergized, so
10   that the body 5 is in a lower limit position as
supported by the inner ring 12b of the protective
bearing 12.   In this state, the position signal Z_s with
respect to the Z-axis direction is read by the target
levitated position setting means 32 of the Z-axis, which
15   feeds a position slightly above the signal position to
the subtracting means 22 as an initial temporary
levitated position, whereby the rotary body 5 is
levitated at the initial temporary levitated position in
the Z-axis direction.   The output (integral output) of
20   the integral operation unit 40 is read at this time and
stored in the flash memory 19 as a first limit position
integral output.

Next, the temporary levitated position in the Z-axis
direction is upwardly shifted by a predetermined

distance at a time, and the shifted position is output to the subtracting means 22. In this way, the temporary levitated position of the rotary body 5 gradually shifted upward. Every time the position is shifted, the

5 position signal Zs and the integral output are read and stored in the flash memory 19 as a corresponding intermediate position and intermediate position integral output.

When the temporary levitated position of the rotary

10 body 5 has been shifted to an upper limit position, the position signal Zs and the integral output no longer alter. This is detected, whereupon the position slightly below the upper limit position is fed to the subtracting means 22 as the final temporary levitated

15 position, whereby the rotary body 5 is levitated at the final temporary levitated position with respect to the Z-axis direction. The corresponding integral output is read at this time and stored in the flash memory 19 as a second limit position integral output.

20 Next, the median of the first limit position integral output and the second limit position integral output is calculated, the integral output most proximate to this median is selected from among the intermediate position integral outputs stored in the flash memory 19,

and the stored value of intermediate position

corresponding to the selected intermediate position

integral output is set as a target levitated position,

whereby the target levitated position in the Z-axis

5   direction is completely set. The target levitated

position thus set is thereafter delivered from the

target levitated position setting means 32 to the

subtracting means 22.

When the rotary body 5 is levitated at a position

10 with respect to the Z-axis direction, the upward

magnetic attraction afforded by the upper axial

electromagnet 26a is in balance with the combination of

the downward magnetic attraction by the lower axial

electromagnet 26b and gravity, In other words, the

15 magnetic attraction by the upper electromagnet 26a is

always greater than that by the lower electromagnet 26b

by an amount corresponding to gravity. The magnetic

attraction of each electromagnet 26 is in proportion to

the square of the magnitude of energizing current of the

20 electromagnet 26 and in inverse proportion to the size

of the gap between the electromagnet 26 and the rotary

body 5. For this reason, there is a position where the

energizing currents of the upper and lower

electromagnets 26 are equal to each other, i.e., a

position there the control current is zero, above the

magnetic central position in the Z-axis direction.   If

the levitated position of the rotary body 5 shifts

upward or downward from this position of zero control

5   current, the control current value varies in proportion

to the displacement of the rotary body 5 from the

position of zero control current.   Further the value of

control current for one of the electromagnets 26 is in

proportion to the output of the integral operation unit

10   40, i.e., the integral output.   Accordingly, when the

levitated position of the rotary body 5 is shifted from

one limit position, i.e., from the lower limit position,

to the other limit position, i.e., to the upper limit

position, the integral output alters linearly.   For this

15   reason, the position corresponding to the median of the

integral output obtained when the rotary body 5 is

magnetically levitated in the vicinity of one limit

position and the integral output obtained when the body

is magnetically levitated in the vicinity of the other

20   limit position is approximately the mechanical central

position, with the result that by taking the position

corresponding to the median as a target levitated

position, the rotary body 5 can be magnetically

levitated approximately at the mechanical central

position.

When the target levitated position with respect to
the Z-axis direction has been completely set, target
levitated positions with respect to the directions of
5   upper and lower X-axes are set at the same time by the
following procedure.

With the rotary body 5 supported at a temporary
levitated position in the Y-axis direction and at the
target levitated position in the X-axis direction, the
10   rotary body 5 is attracted first to a first limit
position in one of the upper and lower X-axis directions
by one of the radial electromagnets 27, 28 in the X-axis
directions of the upper and lower radial magnetic
bearings 7, 8. In this state, the position signal Xs in
15   each X-axis direction is read by the target levitated
position setting means for each of the upper and lower
X-axes, and a position slightly toward the other second
limit position from the position of the signal is fed to
the subtracting means for each X-axis as an initial
20   temporary levitated position, whereby the rotary body 5
is supported at the initial levitated position in the X-
axis direction. The integral output in each X-axis
direction is read at this time and stored in the flash
memory 19 as a first limit position integral output.

Next, the temporary levitated position in each X-axis direction is shifted by the target levitated position setting means toward a second limit position by a predetermined distance at a time, and the shifted

5   position is fed to the subtracting means for each X-axis. In this way, the temporary levitated position of the rotary body 5 in the direction of each X-axis is gradually shifted toward the second limit position, and the position signal Xs for each X-axis and the

10   corresponding integral output are read every time the levitated position is so shifted by the predetermined distance, and stored in the flash memory 19 as the corresponding intermediate position and intermediate position integral output.

15   When the temporary levitated position of the rotary body 5 is shifted to the second limit position, the position signal Xs for each X-axis and the integral output no longer alter. This is detected, whereupon a position slightly closer to the first limit position

20   than the second limit position along each X-axis is fed to the subtracting means as the final temporary levitated position, whereby the rotary body is levitated at the final temporary levitated position in the X-axis direction. The integral output along each X-axis is

read at this time and stored in the flash memory 19 as a second limit position integral output.

Subsequently, the median of the first limit position integral output and the second limit position integral output is calculated for each X-axis, the integral output most approximate to the median is selected from among the intermediate position integral outputs stored in the flash memory 19, and the value of the intermediate position stored and corresponding to the selected intermediate position integral output is set as a target levitated position. In this way, the target levitated position is completely set with respect the direction of each X-axis, and the target levitated position thus set is thereafter delivered from the target levitated position setting means to the subtracting means.

Since each X-axis is horizontal, no force other than the magnetic attraction of the radial electromagnets 27 (28) acts on the rotary body 5 with respect to the X-axis direction. When the rotary body 5 is levitated at a position in the X-axis direction, the magnetic attraction by the electromagnet 27a (28a) at one side is in balance with the magnetic attraction by the electromagnet 27b (28b) at the other side. Accordingly,

when the rotary body 5 is supported at the magnetic

central position wherein the electromagnets 27 (28) are

spaced apart from the rotary body 5 by equal distances,

the energizing current values of the electromagnets 27

5 (28) are equal to each other, with zero control current.

When the levitated position of the rotary body 5 shifts

from the magnetic central position toward the X-axis

direction, the control current value varies in

proportion to the displacement of the rotary body 5 from

10 the magnetic central position. For this reason, the

position corresponding to the median of the integral

output obtained when the rotary body 5 is magnetically

levitated in the vicinity of one limit position and the

integral output obtained when the body is magnetically

15 levitated in the vicinity of the other limit position is

approximately the mechanical central position as in the

foregoing case, with the result that by taking the

position corresponding to the median as a target

levitated position, the rotary body 5 can be

20 magnetically levitated approximately at the mechanical

central position.

When the target levitated positions are completely

set with respect to the Z-axis direction and X-axis

directions, target levitated positions with respect to

the upper and lower Y-axis directions are set at the same time in the same manner as is the case with the X-axis directions. With this, the target levitated position is completely set with respect to every

5 direction of control axis, and the rotary body 5 is set at the target levitated position thus determined with respect to all the control axes and close to the mechanical central position.

The magnetic bearing device is brought out of

10 operation by deenergizing the motor 10 first to stop the rotation of the rotary body 5 and subsequently deenergizing the electromagnets 26, 27, 28 of the magnetic bearings 6, 7, 8. This renders the rotary body no longer supportable by the magnetic bearings 6,7, 8,

15 with the result that the body 5 is supported by the protective bearings 11, 12.

The operation of the magnetic bearing device can be resumed by energizing the electromagnets 26, 27, 28 of the magnetic bearings 6, 7, 8 first to levitate the

20 rotary body 5 at the target levitated position described and driving the motor 10 to rotate the rotary body 5.

When the combination of machine main body 1 and controller 2 has been changed, the target levitated position is set by the procedures described. The rotary

body 5 can thereafter be magnetically levitated approximately at the mechanical central position using the target levitated position.

Not only when the magnetic bearing device is to be operated for the first time or in the event of a change in the combination of machine main body 1 and controller 2, but also when required, the target levitated position can be set anew in the foregoing manner.

In the case where the mechanical central position is not in coincidence with the magnetic central position in the magnetic bearing device described, the rotary body can not be magnetically levitated at the magnetic central position even if the target levitated position is set for the rotary body. If the rotary body is displaced from the magnetic central position, the energizing currents to be supplied to the pair of electromagnets of the magnetic bearing will not be in a linear relationship with the magnetic attraction afforded to result in the likelihood of unstable control. When this gives rise to a problem, there is a need to determine the magnetic central position when the bearing device is to be operated for the first time in order to magnetically levitate the rotary body at the magnetic central position thus determined. A method of

determining the magnetic central position is known as disclosed, for example, in JP-A No. 166139/1997. With this disclosed method, the rotary body is temporarily levitated at a predetermined provisional levitated

5   position such as the central position relative to the sensors, and speculation is made about the posture of the rotary body as installed and the magnetic central position from the energizing currents then flowing through the pair of electromagnets of each magnetic

10   bearing. The postures of the installed rotary body include vertical postures wherein the body, i.e., the Z-axis, is vertical, and horizontal postures wherein the Z-axis is horizontal. The vertical postures include an erect posture wherein the positive direction of the Z-

15   axis is up, and an inverted posture wherein the positive direction of the Z-axis is down. The horizontal postures include an X-axis erect posture wherein the X-axis is vertical and the positive direction of the X-axis is up, an X-axis inverted posture wherein the

20   positive direction of the X-axis is down, a Y-axis erect posture wherein the Y-axis is vertical and the positive direction of the Y-axis is up, and a Y-axis inverted posture wherein the positive direction of the Y-axis is down. A suitable posture is selected for installation

in conformity, for example, with the use of the bearing
device. The controller is used is used for making
speculation about the posture of installation and the
magnetic central position. For this purpose, the

5 controller has stored in its memory data (speculation
data) representing the relationship of the energizing
currents through the pair of electromagnets for each
control axis with the position of the rotary body with
respect to the direction of the control axis to

10 speculate about the magnetic central position from the
electromagnet energizing currents based on the data.
However, the speculation data differs for different
installation postures of the rotary body, so that the
controller needs to have stored therein speculation data

15 as to all installation postures, while the controller is
unable to determine the magnetic central position in the
case where the rotary body is installed in a posture for
which no speculation data is stored as in the case where
the Z-axis is installed obliquely. Once the magnetic

20 central position is determined, the rotary body can be
levitated at the magnetic central position insofar as
the combination of machine main body and controller
remains unchanged even if the posture of the installed
rotary body is changed. However, in an event of a

change in the combination of machine main body and

controller, the magnetic central position in the machine

main body is not set in the new controller, so that the

controller as it is fails to magnetically levitate the

5   rotary body at the magnetic central position.

Accordingly, there arises a need to determine the

magnetic central position anew, whereas if the rotary

body is installed in a posture for which no speculation

data is stored in this case, it is still impossible to

10   determine the magnetic central position.

     With the magnetic bearing device described, however,

the rotary body 5 can be magnetically levitated at the

magnetic central position by the following procedure

regardless of the installation posture thereof.

15   In this case, memory means such as a memory is

provided in the machine main body 1 for storing the

shift of the magnetic central position from the

mechanical central position. On the other hand,

speculation data for at least one installation posture

20   is stored in the flash memory 19 of the controller 19.

The machine main body 1 is first installed in the

posture according to the stored speculation data. Next,

speculation is made about the mechanical central

position, and the rotary body 5 is temporarily levitated

in this position as a provisional levitated position.

This can be done, for example, by the foregoing method

of setting the target levitated position.   Since the

rotary body 5 is thus magnetically levitated

5   approximately at the mechanical central position, the

energizing current values of the pair of electromagnets

of each of the magnetic bearings 6, 7, 8 are detected,

and speculation is made about the magnetic central

position on each control axis from the detected current

10   values based on the speculation data.   The method

disclosed in JP-A No. 166139/1997 can be used for this

procedure.   When the speculation has been made on the

magnetic central position in this way, the value of the

magnetic central position in the direction of each

15   control axis is stored in the controller 2, and the

value of the difference or shift of the magnetic central

position from the mechanical central position on each

control axis is stored in the memory of the machine main

body 1.

20   The magnetic bearing device can be thereafter

operated by the combination as it is or by a changed

combination of machine main body 1 and a controller 2.

The posture of the machine main body 1 installed can be

changed when so required.

When the combination of machine main body 1 and
controller 2 remains unchanged, the rotary body 5 can be
magnetically levitated at the magnetic central position
using the value of magnetic central position stored as

5   it is in the controller 2 regardless of the posture of
the installed machine main body 1. In this case, the
controller 2 needs only to have stored therein the
speculation data as to at least one installation
posture, and it is not always necessary fro the

10   controller to have stored therein the speculation data
relating to all the installation postures.

In the event of a change in the combination of
machine main body 1 and the controller 2, speculation is
first made about the magnetic central position as will

15   be described below, and the rotary body 5 is thereafter
magnetically levitated at the magnetic central position
using the value of the magnetic central position.
First, the machine main body 1 is installed in a posture
for use. The mechanical central position is then

20   determined in the same manner as the foregoing method of
setting the target levitated position, and the
mechanical central position on each control axis is
stored in the controller 2. For each control axis, the
value of displacement or shift stored in the memory of

the machine main body 1 is then added to the mechanical

central position thus determined to thereby determine

the magnetic central position. The rotary body 5 is

thereafter magnetically levitated at this magnetic

5   central position as the target levitated position. In

this case, the mechanical central position can be

determined by the foregoing method of setting the target

levitated position regardless of the posture of the

machine main body 1 installed. Furthermore, the

10   magnetic central position can be determined from the

mechanical central position by a simple addition

calculation. Accordingly, even in the event of a change

in the combination of machine body 1 and controller 2,

the magnetic central position can be determined easily

15   to magnetically levitate the rotary body 5 at the

magnetic central position regardless of the installation

posture of the machine main body 1. Further since the

new controller 2 need to make speculation about the

magnetic central position based on the energizing

20   currents of the electromagnets as described above, there

is no need to store the speculation data described.

Although the foregoing embodiment is a magnetic

bearing device of the inner rotor type wherein a rotary

body rotates inside a casing which is a fixed portion,

the present invention is applicable also to magnetic

bearing devices of the outer rotor type wherein a rotary

body is rotatable externally of a fixed portion.

The foregoing embodiment is a magnetic bearing

5 device of the vertical type wherein the rotary member is

disposed vertically, whereas the invention can be

embodied also as magnetic bearing devices of the

horizontal type which have a horizontal rotary body.